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Quantum Image Processing and Storage with Four-Wave Mixing

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Final report on AFOSR grant #FA9550-13-1-0035
"Quantum Image Processing and Storage with Four-Wave Mixing"

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Abstract

Interest in the field of quantum optics has largely been motivated by demonstrating the unique features of the quantum world in the context of light. Taking advantage of these quantum properties of light to make advances in the context of metrology and measurement science has been the practical goal of our lab, and of the work supported under this grant. In particular, while many groups have worked toward demonstrating quantum features of light and how they can be used to advantage in fundamental scientific as well as some practical experiments, it has often been in the restricted context of a single spatial mode. In imaging terms this means a single "pixel" in an optical system. Our goal has been to attempt to expand the quantum advantages into multi-pixel imaging applications as well as to improve and simplify some of the single-spatial-mode applications of squeezed light through the use of four-wave mixing (4WM) in atomic vapors. We have worked to study the propagation of quantum correlations, improve low-frequency squeezing, demonstrate phase-sensitive optical amplification and its applications, and demonstrate a method for calibration of the absolute quantum efficiency of photodiodes. We have demonstrated intensity-difference (two-mode) squeezing to frequencies below 50 Hz, which will be used for photodetector calibration and imaging experiments. We have studied the propagation of quantum information through a phase-sensitive optical amplifier and used this amplifier to implement a "perfect detector" for a single-quadrature signal. We have also used the phase-sensitive amplifier to characterize phase and amplitude modulation in an optical signal.

Introduction

Nonlinear optical processes have been shown to be able to lead to optical states with interesting quantum mechanical properties. These states have noise and correlation properties that can improve upon the best measurements physically possible with "classical" states of light. In particular "squeezed states" of light can have sub-shot-noise fluctuations that can lead to better measurements and "two-mode" squeezed states can produce correlations between two beams such that, even though the beams themselves have noise properties that are not very special, the noise in the two beams is so highly correlated that again, sub-shot-noise measurements can be made using these states.

Our laboratory pioneered a technique for generating squeezed states of light near a Rb atomic resonance that has proven to be fairly easy to implement and robust to operate, and has been adopted by a number of groups around the world. Using small (~1cm long) vapor cells warmed to about 120C and light from diode or Ti:sapphire lasers we are able to make measurements with up to a factor of 10 improvement over conventional "classical" optical techniques. In addition, since our technique does not require the use of an optical cavity to enhance the field strength, it is easy to apply this to many spatial modes in parallel. Hence we can perform imaging experiments with squeezed light. We continue to explore the applications of this technique and summarize here our accomplishments during this grant period.

Our recent progress was somewhat limited by the fact that we packed up our labs and moved them from the NIST campus to the campus of the University of Maryland, where new facilities at the Joint Quantum Institute were made available. This, inevitably, disrupted our experiments for a good part of a year. We also spent a good deal of time engineering better low-frequency performance into our squeezed-light source. While this will be very useful going forward, it was not felt that this was, by itself, publishable work at this time.

Our work has concentrated on “fast light” and communications, phase-sensitive amplification, sensitive imaging and detector calibration techniques, and optical storage and memory. In addition, we have studied squeezed light in interferometric applications. During the grant period one graduate student, Jeremy Clark, finished with a PhD [1] in November 2013.

Fast Light and Information Propagation

Our work on fast light looks at the propagation of quantum information through media with both normal and anomalous dispersion. The motivation was to be able to investigate the propagation of signals in “fast light” conditions more precisely by using the better-than-shot-noise correlations that we obtain with quantum-correlated twin beams of light generated by 4-wave mixing. It turns out that we can do a good job of looking at the physics of fast light, as well as investigate the transport of quantum information in our experiments. We have examined the advance of classical signals under anomalous dispersion conditions [2], but we have also looked at the advance and accompanying degradation of quantum correlations, or information, in such fast light media. We could see that the dispersion required for fast light necessarily comes with added noise, either from gain or loss, and this works to limit the fidelity and advance of quantum correlations [3]. After that an important step was to start looking at the quantum

mutual information in the system, and the temporal advance of that particular measure [4]. This is also related to our previous work on "quantum discord," [2], in that the quantum mutual information can be used to quantify both classical and quantum information in such a system.

We are now attempting to repeat this sort of measurement with a phase sensitive amplifier (PSA). In the above-mentioned experiments we used a phase insensitive amplifier (PIA) based on 4-wave mixing (4WM) gain to generate the anomalous dispersion region for fast light. The noise associated with the gain can be calculated, and it seems to be just enough to prevent the advance of any signal. This brought up the question of just what happens if we use a PSA based on the same 4WM interaction to generate phase shifts, instead of a PIA. A phase-sensitive amplifier can perform noiseless amplification. Even though this is true for just one phase-quadrature of the signal, it would seem disturbing if we had the same dispersion as in the PIA case, but no noise, and if we were thus able to advance a signal in this situation. Since we know that we can have noiseless amplification with a PSA, it would seem to imply that in this case we cannot have anomalous dispersion - or any dispersion, by symmetry arguments.

Unfortunately the PSA is much more complicated than the PIA in its operation. Aside from being limited to low gain to prevent parasitic phase-insensitive 4WM processes from dominating, it is capable of, for instance, converting phase modulation into amplitude modulation, and consequently it requires very careful calibration of the input signals in an experiment.

Phase Insensitive Amplifier (PIA)

We have studied the effect of fast and slow light media (anomalous and normal dispersion) on the transmission of information, in particular, quantum information. While a number of authors have carried out similar experiments in the past, looking at the movement of classical information, we took an information-theoretic definition of the mutual information between two quantum-correlated beams and examined the effects of dispersion on this particular measure. One beam acts as a reference and the second is passed through either a fast or slow light medium before measurement.

While the anomalous dispersion could advance the peak of the normalized intensity correlations, we found that the mutual information, properly defined in an information-theoretic way, was degraded by added noise to the extent that there was never any additional or "extra" information that arrived before the corresponding information in the reference trace. That is, while the peak of information arrival can be advanced, it will be degraded to such an extent that it cannot rise above the value of the reference trace, as shown in Fig. 1, below. When the dispersive medium was tuned to produce slow light with a similar amount of added noise it was found that there was a substantial delay of both the peak as well as the entire trailing edge of the mutual information curve.

The addition of noise seems to be the mechanism by which nature prevents the early ("faster-than-light") arrival of information. Fundamentally, however, there is still something to understand in the difference between fast light and slow light. The change of sign in the slope of the dispersion seems to affect more things than simply altering the group velocity. Although it is comforting (and not unexpected) that causality is not violated in this situation, we would still like to be able to point to the mathematical/

physical difference that keeps information from advancing but not from being delayed, in order that we understand it, and perhaps be able to take advantage of it. Thus, there remains more to investigate here.

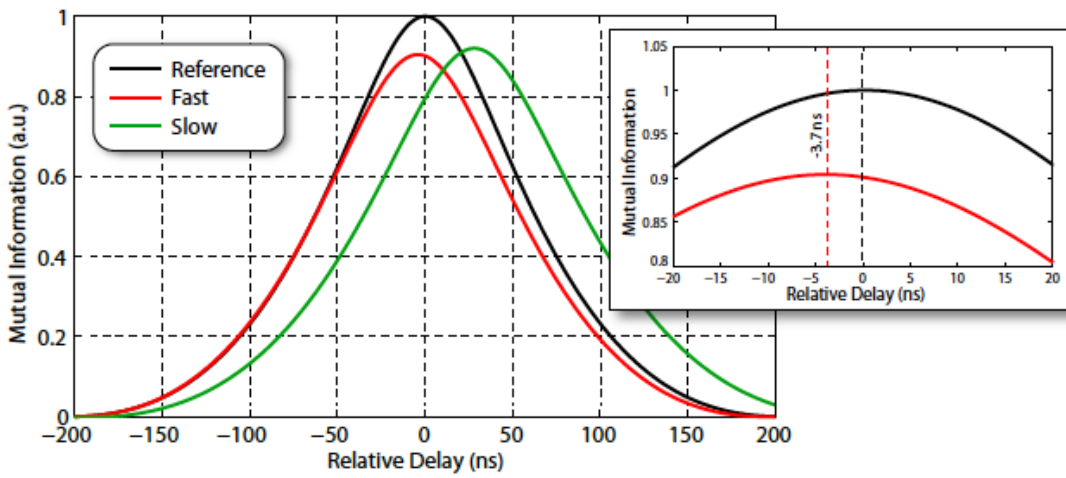

Figure 1 - Plot of the mutual information as a function of delay for a continuous-wave signal. Black is the reference mutual information curve without dispersive media, red shows the advance of the mutual information under fast light conditions, and green shows the delay of the mutual information under slow light conditions when the degradation of the information is similar to that found under the fast light conditions.

In the above measurements we used a phase-insensitive amplifier, where with moderate gain we could obtain either "fast light" or "slow light" dispersive conditions. We then used the same 4WM process to create the dispersive medium. An anomalously-dispersive medium and a normally-dispersive one can be derived from the same 4WM gain process at different detunings. Knowing that we could create a phase-sensitive amplifier (PSA) from the same 4WM process brought up a question as to how such a PSA would behave, both in information advance and dispersive properties.

Phase-Sensitive Amplification

If all four of the "waves" in the 4WM process are injected there is no longer the freedom for an "idler" or conjugate beam to adapt in order to achieve the maximum gain condition. Thus, with the same geometry as the twin-beam, phase-insensitive case, if one pumps on what would have been the probe and conjugate frequencies and injects a signal at the center frequency, along what would have been the pump direction (see Fig. 2), one can construct a phase-sensitive amplifier. This amplifier will amplify one quadrature (say, a cosine wave) while de-amplifying the orthogonal quadrature of the input (the sine wave). An interesting feature of this amplifier is that at the maximum amplification or de-amplification phases the amplifier will be noise-free. That is, one can obtain noiseless amplification of the cosine quadrature and noiseless de-amplification of the sine quadrature of the input. We have spent some effort investigating this phase-sensitive configuration in a number of experiments.

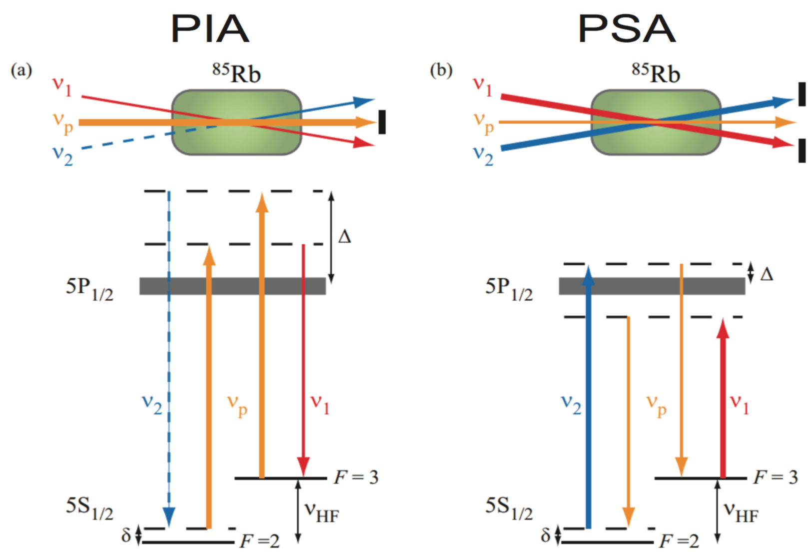

Figure 2. PSA/PIA level diagrams and geometry. (a) In the case of the phase-insensitive amplifier the pump and only one of the sideband frequencies are injected. The vacuum input on the remaining mode allows for the phase insensitivity. (b) In the phase-sensitive case all of the required fields are injected and the relative phases of these fields are important. The detunings of the beams from the atomic resonance also need to be different to obtain the best PSA operation.

If the phase-sensitive amplifier (PSA) is operated in its noise-free maximum amplification or de-amplification conditions, how is causality preserved? Without noise, can there be any dispersion? We are exploring this now, and it does seem to be true that, even though the gain line is identical for the cases of the PSA and PIA, the dispersion relationship is very different, and indeed it is phase-dependent for the PSA.

The behavior of the PSA is sufficiently unfamiliar that it required a study of its input-output characteristics in the case of a modulated signal before we could really understand how to study the mutual information transmission for this device. We found that intentionally intensity-modulating the input using an acousto-optical modulator (AOM) often led to spurious signals at the output due to the unintentional phase modulation that also came from the AOM. This led to a study of the phase modulation that is also imposed when using a simple optical chopper.

In an attempt to understand the input-output relation of the PSA we tried to inject a simple amplitude-modulated signal into it. Unfortunately, the PSA can interconvert phase and amplitude modulation, leading to unexpected signals if the input is not sufficiently well-characterized. Our first reaction to the residual phase modulation on the AOM was to switch to using a mechanical chopper to intensity-modulate the beam. Unfortunately, a mechanical chopper also imposes a large phase modulation onto a beam. While at first glance this may seem surprising, if one thinks of pushing a card into a beam, the changing diffraction around the edge of the card clearly implies phase variations. If one thinks of pushing a card into, say a TEM 01 mode, which has positive- and negative-phased lobes, first cutting off one lobe, and then the other, one will clearly impose dramatic phase shifts into the transmitted portion of the beam. We found that the PSA itself can be used to detect such phase modulations.

While the phase modulation on a beam is often detected using homodyne detection, this sort of phase modulation induced by diffraction is difficult to measure via homodyne unless the local oscillator beam is similarly re-shaped and a transient signal is studied. Our PSA, however, will react to whatever sort of beam shape is input, and the phase and amplitude modulation at the output can be used as a diagnostic for the modulation on the input beam. The principle is to look at the dc and the ac gain for the amplifier. A constant input with no modulation will result in a fixed-gain, dc output; in the PSA the relative phase of the input matters as well, so that as the phase is varied the dc gain varies too. If there is only amplitude modulation present then the ac gain at the modulation frequency will track the dc gain. If there is phase modulation present then the interconversion changes this. By injecting a sine-wave oscillation on top of a dc signal we can measure both the ac and dc gains directly, as a function of phase, and the results can be seen in Fig. 3.

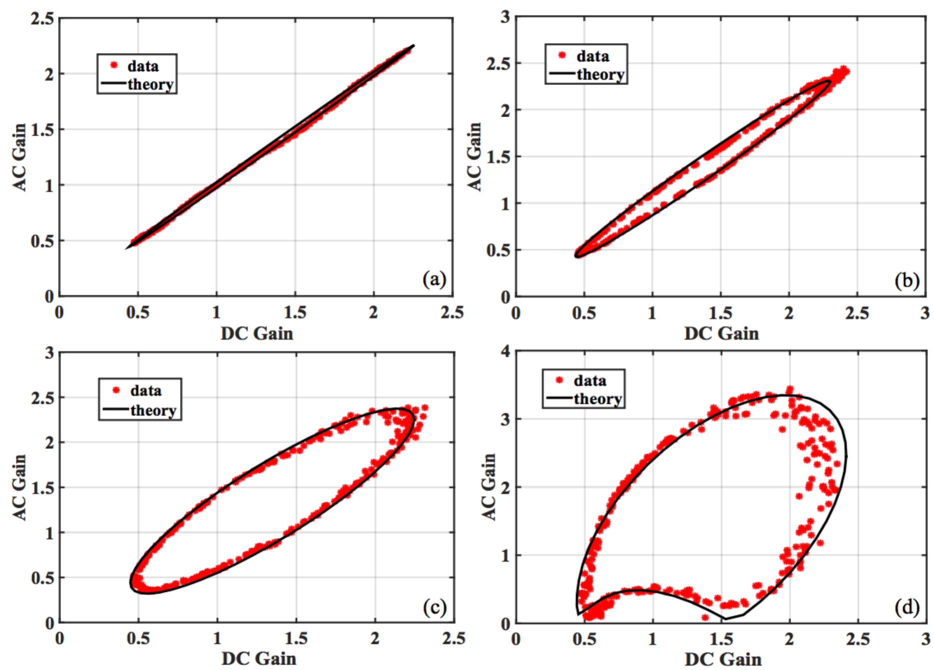

Figure 3. AC gain versus DC gain for an optical signal modulated with an acousto-optic modulator and amplified in an optical phase-sensitive amplifier. The different plots are for different mixtures of AM and PM due to the AOM alignment. Each plot is parametric with respect to the phase of the PSA. The solid curves are theoretical fits. (a) $P/A = 0.02$, (b) $P/A = 0.13$, (c) $P/A = 0.42$, (d) $P/A = 1.59$, where P/A represents the ratio of the amplitudes of the phase and amplitude modulations of the input.

We have compared the measured ratio of phase-to-amplitude modulation measured by the PSA to measurements made by homodyne detection and found a good correlation between them. The PSA can thus be used as a diagnostic tool to measure the amount of phase modulation on a beam. It can also be used in situations where the homodyne technique is problematic, such as in the case of an optical chopper. Here one must define what is meant by ac gain, and we take the transient part of the gain as the chopper moves from fully blocking the beam to fully passing the beam as the ac part of

the signal. As seen in Fig. 4, if there is a large phase modulation present the transient overshoot of the output intensity from the PSA signifies its presence [5].

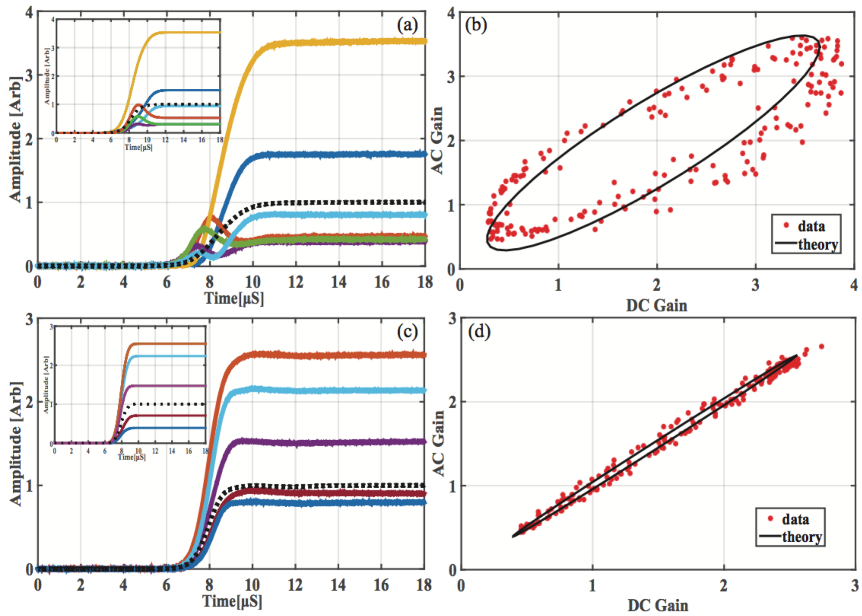

Figure 4. Phase modulation measurements for two different chopper alignments using the PSA scheme. (a) and (c) show raw data from a tilted chopper alignment and optimal chopper alignment, respectively. Inset theory curves are shown as examples to demonstrate curve shapes for the fit parameters and do not necessarily match the PSA phases of the individual data curves shown. (b) and (d) show AC gain vs. DC gain for the tilted chopper alignment, and optimal chopper alignment, respectively. The dashed curves in (a) and (c) are the error functions when the PSA is off. The solid curves in (b) and (d) are theoretical fits where $P = 0.7$ and $P = 0.15$, respectively.

Now that we understand and can control the PSA somewhat better for classical signals we are able to move on to our intended experiments measuring the signal advance or delay for quantum correlations through the PSA.

Given that the added noise seems critical to maintaining causality, an amplifier without noise would seem to be able to threaten this feature. Our phase-sensitive amplifier (PSA) performs noiseless amplification for a single signal quadrature, while utilizing the same gain feature as the phase-insensitive amplifier that we used to create the dispersion in the experiments above. In our preliminary experiments it would seem to be that the dispersive properties of the PSA vary with the phase, and for noiseless amplification or de-amplification the dispersion goes to zero. At phases between these conditions, noise is added to the signal and either phase advance or delay (anomalous or normal dispersion effects) can be obtained. We can also explore the fundamental noise limits and performance of the PSA in this way.

One can also look at the PSA "dispersion" from a different point of view. The PSA will (noiselessly) amplify a particular quadrature, and deamplify the orthogonal quadrature. If one decomposes an arbitrary signal into these two quadratures, then there is never any noise added to these quadrature components of the signal, but if the signal is not confined to one of the "natural" quadratures defined by the PSA then the signal will

be distorted by the differential amplification and deamplification of these components. In this sense there is no "dispersion" in the PSA, as such, but rather an apparent phase advance or delay that depends on the gain of the PSA and the original mixture of the "natural quadratures" of the PSA that make up the signal. If a signal is introduced that is completely into one of the natural amplification or deamplification quadratures it remains there, and exits with no phase advance or delay. If it enters in a superposition of these quadratures, it exits rotated toward the gain quadrature and the amount of the phase advance or delay depends on both the input superposition and the gain (see Fig. 5). This behavior indicates a phase shift that varies with the input phase of the signal, and is unlike what we would normally call "dispersion", where the phase shift is frequency-dependent, but independent of phase. Both are present in a PSA.

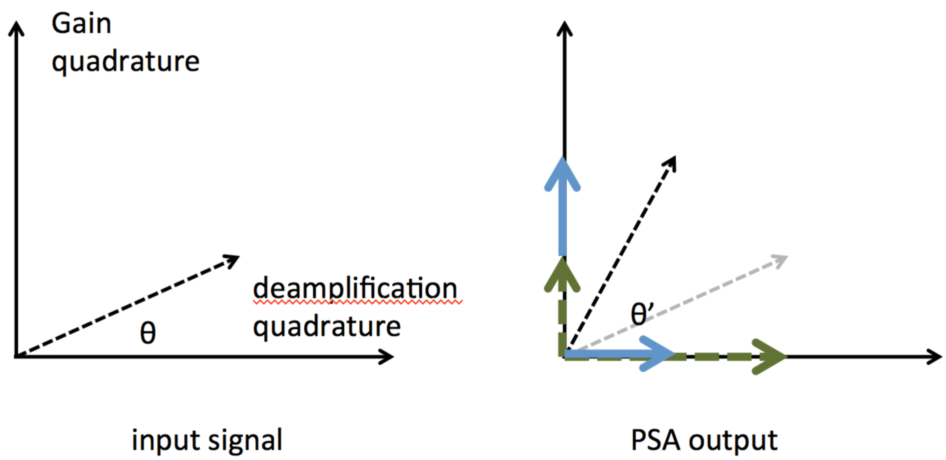

Figure 5. Phase rotation with gain in a PSA. If the signal into a PSA is not along either the natural amplification (gain) or deamplification quadrature directions initially the differential amplification/ deamplification of these quadratures will produce an apparent phase advance or delay for the signal at the output. In the right panel the input components (green) are transformed at the output (blue) to produce an apparent phase shift in the signal from θ to θ'.

While the procedure for extracting the mutual information between two Gaussian beams, such as we have, is well established, this gives the information carried by both quadratures of both beams, not just one. Since the PSA will treat the two quadratures differently, we are investigating the measurement of single-quadrature mutual information. Classically this is straightforward, but we are trying to make sure that we are treating the quantum problem properly. Similarly, we wish to measure the quantum discord (difference between classical and quantum information) under these conditions. We are just at the point where we can begin these measurements.

The logical result seems to be that there is no "dispersion" for a PSA when it is operated at the noiseless amplification or de-amplification phases. If one looks at the apparent phase advance or delay in propagating through a PSA (see Fig. 5) we see that the amplification and de-amplification of the orthogonal quadratures produces an effect that creates an apparent phase rotation. The phase of the beam is, however, not so much advanced or delayed, but rather has its components amplified and attenuated differentially.

Perfect Detector

Using the same experimental configuration as we will use to investigate the transport of mutual information we are also able to construct and test "perfect" homodyne detectors. For the detection of a particular quadrature we can, in principle, noiselessly amplify a signal before attenuating it. One can consider an optical detector with less than 100% quantum efficiency as equivalent to a perfect detector with a lossy beamsplitter element in front of it. One can then recover a perfect detector by noiselessly amplifying the detected quadrature, overwhelming the subsequent loss, before the signal reaches the imperfect detector. We are in the process of measuring this "approach to perfection" in the lab now, although we have a relatively limited range over which to do this (we can obtain noiseless amplification only for gains less than about 5).

The experimental set-up for investigating "perfect detectors" or mutual information in a PSA is shown in Fig. 6. While one cannot, unconditionally, noiselessly amplify an arbitrary quantum state (both quadratures), we have seen that it is possible to build a noiseless amplifier for a signal in a single quadrature using a PSA. A homodyne detector looks at a single quadrature signal that is determined by the phase of the local oscillator. Such detectors are often used in the detection of squeezed light or other non-classical states of light, or in quantum key distribution (QKD) systems. If the final detector is not 100% efficient, due to the photodetector itself, or imperfect mode-matching with the local oscillator, then this will reduce the amount of squeezing that is measured, or the fidelity of either QKD transfer or the measurement of an arbitrary quantum state. The homodyne detector can be made effectively 100% efficient, however, by including a PSA that noiselessly amplifies the quadrature that is to be measured.

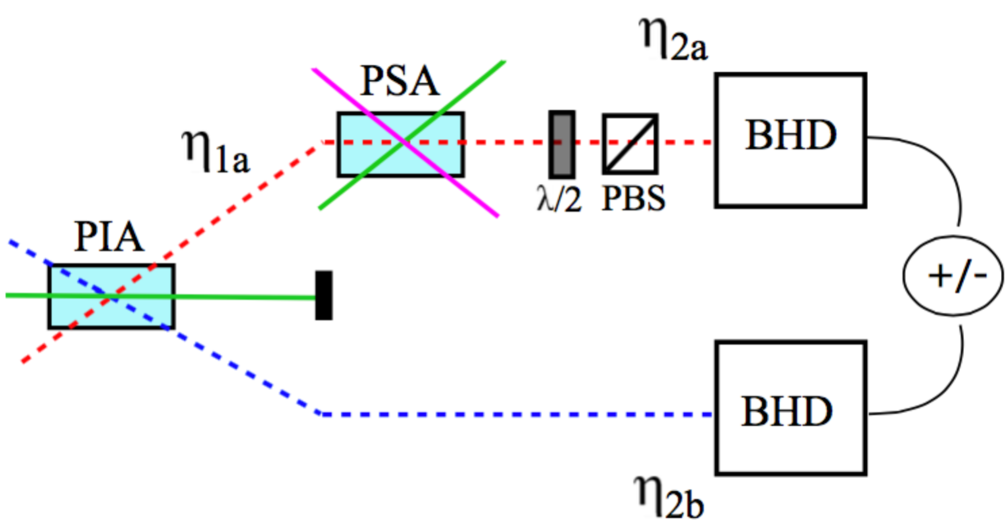

Figure 6. Experimental set-up for both perfect quadrature detection and for measuring the advance or delay of mutual information through a PSA. The PSA can compensate for loss that occurs after that point in the beam path and effectively create a perfect detector. For testing the advance or delay of quantum information we can measure the quantum mutual information with and without the PSA in one of the beam paths and for different PSA relative phases. BHD = balanced homodyne detection, PIA = phase insensitive amplifier, PSA = phase sensitive amplifier, PBS = polarizing beamsplitter.

The PSA in Fig. 6 above can be considered to be part of the detector, compensating for any loss that occurs after that point in the system (including the photodetector quantum efficiency). This compensation is somewhat "stochastic," but becomes perfect in the limit of large gain. If we imagine that the upper homodyne detector in the figure has 50% quantum efficiency, then we can insert a (noiseless) gain of 2 PSA in front of the homodyne system to partially compensate for this. The reason that the compensation is only partial is that the loss is stochastic – each signal photon is not cut in half, but rather, on average half of the photons are lost. If we were to noiselessly perfectly duplicate each photon, and then randomly lose half of them, we still would not return to the original signal. In a rough way of thinking, if we started with one photon, generated a second one, and then put this through a 50/50 beamsplitter, we might get one, both, or neither of the photons through, but on average the fidelity of the signal would generally be better (and the signal would be larger) than if we had not done this. In the limit of large amplification this operation would essentially generate a classical signal that could be cut in half by the beamsplitter with the addition of a negligible amount of noise, and that is the principle at work here.

In our implementation we create quantum-correlated beams using the 4WM PIA source, and can change the effective quantum efficiency of the detector by inserting loss between the PSA and the homodyne detector as in the set-up in Fig. 6. We can then try to compensate for this by changing the gain in the PSA and examine how well the quantum correlations between the twin beams from the source survive. When the gain is higher than the loss in the testing arm we need to renormalize the size of the signal in order to look at the correlations properly. In Fig. 7 we show the measured squeezing levels for the amplified quadrature, with and without the PSA on, for three different values of the gain (gain = 2, 3, and 4). One can see that, in particular for higher gains, the

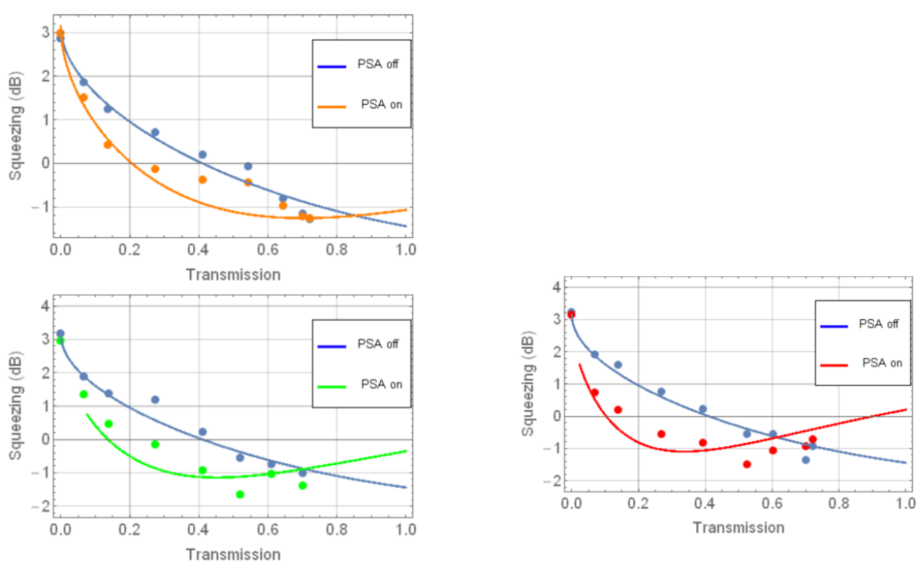

Figure 7. Squeezing level with PSA on or off for three gains G = 2 (top left), 3 (bottom left), 4 (right). Circles are experimental averages of 50 shots from the spectrum analyzer. Curves are simulations experimentally measured loss parameters. The squeezing maximizes at transmissions of less than 1 because of the imbalance between the beams; if the detector gains were to be adjusted to optimize squeezing the improvement would improve monotonically with the transmission.

squeezing can be reduced due to the fact that the signals arriving at the two detectors become quite unbalanced. If we had compensated for this difference in the squeezing measurements by adjusting the relative electronic gain of the detectors much of this squeezing could be recovered. An improved set of "perfect detector" measurements are now being made and an article is being prepared for publication on this topic.

Single-Mode Squeezing from a PSA

We have also analyzed and published some measurements of the rotation of the noise ellipse in the generation of single-mode vacuum quadrature squeezing. The PSA, operated with a vacuum input, naturally produces "single-mode squeezed vacuum" in multiple spatial modes. Here "single-mode" refers to the type of squeezing – for instance intensity squeezing in a single beam – and differentiates it from the twin-beam or "two-mode" squeezing that we generate in the PIA. This single-mode squeezing is the type of squeezing that one would use to inject into an interferometer such as LIGO, to improve its sensitivity.

We have discovered that the squeezing axis or quadrature which is most strongly squeezed changes with frequency in our system due to the differential gain for the upper and lower squeezed sidebands in the 4WM process [6]. In principle this behavior would allow one to tailor the noise frequency spectrum of the squeezed light to match the noise spectrum of the interferometer, optimizing which quadrature is squeezed as a function of frequency. This is of particular interest to the gravitational wave interferometer community, as it would allow them to reduce shot noise (at the expense of radiation pressure noise) at high frequencies and also alter the squeezing quadrature to reduce radiation pressure noise in the interferometer at low frequencies. While we were the first to report such a rotation of the squeezing ellipse as a function of frequency for vacuum squeezing, the degree of squeezing that we can achieve in the foreseeable future is only about -4 dB, which limits its usefulness for purposes such as gravitational wave interferometry.

Phase Sensitive Amplification of Images

We have performed a number of different types of measurements with our phase sensitive amplifier. Earlier we showed that we could noiselessly amplify images using a PSA based on 4WM. Those measurements used multi-spatial-mode images that were modulated, as a whole, in time. We demonstrated that the signal-to-noise on the modulation was preserved after amplification [7]. While this does demonstrate a useful property of the PSA, it is not the usual way in which one would like to implement imaging with a PSA. We are presently working on taking camera images before and after amplification with the PSA, and trying to demonstrate the preservation of the pixel-by-pixel spatial (instead of temporal) signal-to-noise ratio.

In order to make measurements of images in a "normal" fashion – that is, using an imaging detector such as a CCD camera – we have had to improve our ability to obtain squeezing at very low detection frequencies. A camera integrates the image during a window of time, and the squeezing in the resulting image is proportional to the squeezing in the optical beam, weighted and integrated over the frequencies represented in the time window. Thus, large excess noise at very low measurement frequencies, which is typical

in our system, can overwhelm good squeezing at higher frequencies. Getting rid of this technical noise has been a major goal of our work.

With the ability to limit the technical noise at low frequencies discussed in the next section we can now optimize the set-up for imaging. We will use a relatively large-aperture Pockels cell to chop out pulses from the twin beams and direct them to a high-quantum-efficiency camera (approximately 90% quantum efficiency at 800 nm). Using this we should be able to perform imaging detection of small absorbing objects. An obvious candidate target would be a rubidium Bose-Einstein condensate. In other respects small biological objects are also reasonable targets, although absorption imaging may not be as effective, as they are mostly transparent at these wavelengths and would require an interference scheme to detect phase shifts instead.

Low Frequency Squeezing

Low frequency squeezing refers to having reduced noise at low measurement frequencies, in particular, in twin-beam, intensity-difference squeezing measurements. This is important because many applications either require low frequencies directly (for instance photodiode calibrations at low frequencies) or signals integrated over low frequencies (integrating on a camera). While photodiode calibrations are important and are particularly relevant to the NIST mission, camera imaging (taking differential images, one with an absorber in the beam, and a twin-beam image without) is especially appealing because it would allow us to rather quickly apply sub-shot-noise imaging techniques to a variety of different targets.

Given that we are working with Rb vapor to generate twin beams, the most obvious target for sub-shot-noise imaging is atomic Rb - in particular for Rb BEC absorption imaging. While this is not widely applicable outside of scientific laboratories, it would probably be one of the places where such a technique might be quickly adopted. On the other hand, given that 795 nm is generally a good wavelength for biological imaging, it would also allow us to quickly try to demonstrate some low-resolution but high-sensitivity imaging in this context, to see how it might be applied.

If one wants to take twin-beam images on a CCD camera, one has to integrate over the light fluctuations from dc up to the inverse of the shutter time. Unfortunately, there is always a very large noise spike (technical noise) near dc that frustrates a straightforward image subtraction (see Fig. 8). The frequency range for the squeezed sidebands is limited in our case on the high frequency end by the bandwidth of the 4WM gain. Typically this is about 20 MHz for our usual operating parameters. On the low frequency end we have generally been limited by laser performance. A commercial Ti:sapphire laser was able to "easily" get us squeezing down to 100 kHz, and by turning off the locking electronics and allowing the laser to drift, we obtained squeezing down to 2 kHz (presumably the locking electronics disturbed the low frequency performance of the laser) [8]. Even this was not low enough to suppress the contribution of the low-frequency noise peak by a large enough factor for image subtraction. Several years ago, using a diode laser and semiconductor tapered amplifier we were able to get squeezing only down to 0.5 MHz, which we attributed to the intrinsic noise of the diode laser. In the past year, however, we have been able to obtain squeezing down to below 50 Hz with a similar system. We are systematically investigating what parameters (laser linewidth, detuning, intensity and alignment parameters) affect the low frequency performance. It is

now clear that we can do very well with our current system, and it is important that we are able to do this with diode laser systems for both cost and portability considerations.

One of the first projects where we will apply this low-frequency squeezing will be analog photodiode calibrations at the mW level. Current photodiode efficiency measurements are performed at approximately 200 Hz (metrological silicon photodiodes tend to be high-efficiency, large-area diodes with thick active areas to capture and absorb all of the incoming light, and consequently have large capacitance and operate at low frequency), and we will now be able to directly compare our results with current NIST calibrations.

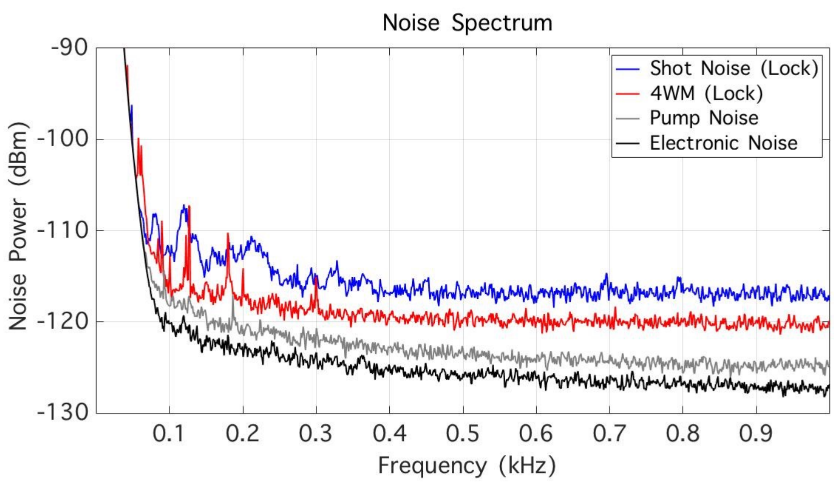

Figure 8 - Low frequency spectrum of squeezing showing the electronic noise, scattered pump light noise, intensity-difference noise from the 4WM-generated twin-beams, and the shot noise levels (bottom to top). Some amount of low-frequency technical noise contaminates both the 4WM and shot noise traces.

An obvious possibility for what has limited the squeezing at low measurement frequencies is that the pump laser linewidth affects the ground state decoherence rate, and thus the squeezing levels. If a ground-state coherence is established by the scattered light fields, then an interruption of the pump phase will perturb this coherence until the phase relationship is reestablished. Thus, linewidth-narrowing should help improve low-frequency squeezing if pump phase interruptions are a major problem. We used polarization spectroscopy and a fast electronic feedback system to both lock and narrow the laser frequency, as indicated in Fig. 9. The linewidth is measured using a self-heterodyne method [9] where the light from the laser that is frequency-shifted and passed through 10 km of optical fiber is beat against light directly from the laser. This lead to a measured laser linewidth of approximately 15 kHz, versus the 200 kHz of the un-narrowed laser. As shown in Fig. 10, this does lead to an improvement in the squeezing level at frequencies below 20 kHz, however it is not always a significant effect, especially at the lowest frequencies. Thus, we needed to investigate other causes of reduced squeezing as well.

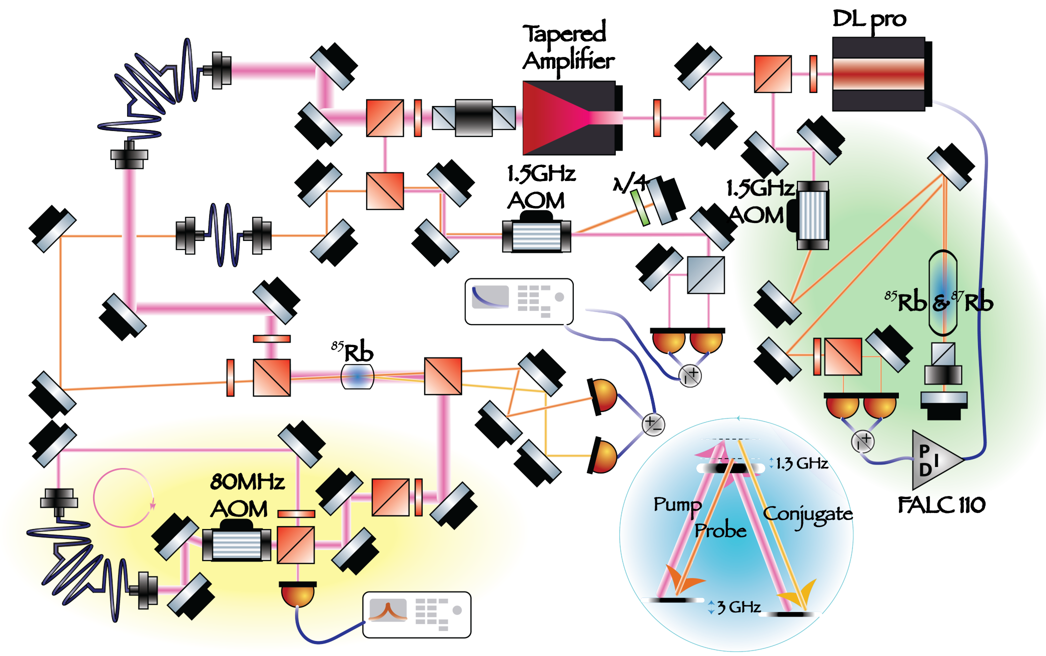

Figure 9. Experimental set-up for generating low-frequency squeezing that includes locking and narrowing the laser with polarization spectroscopy (shaded area at right) and linewidth measurement with a self-heterodyne set-up (shaded area at bottom left).

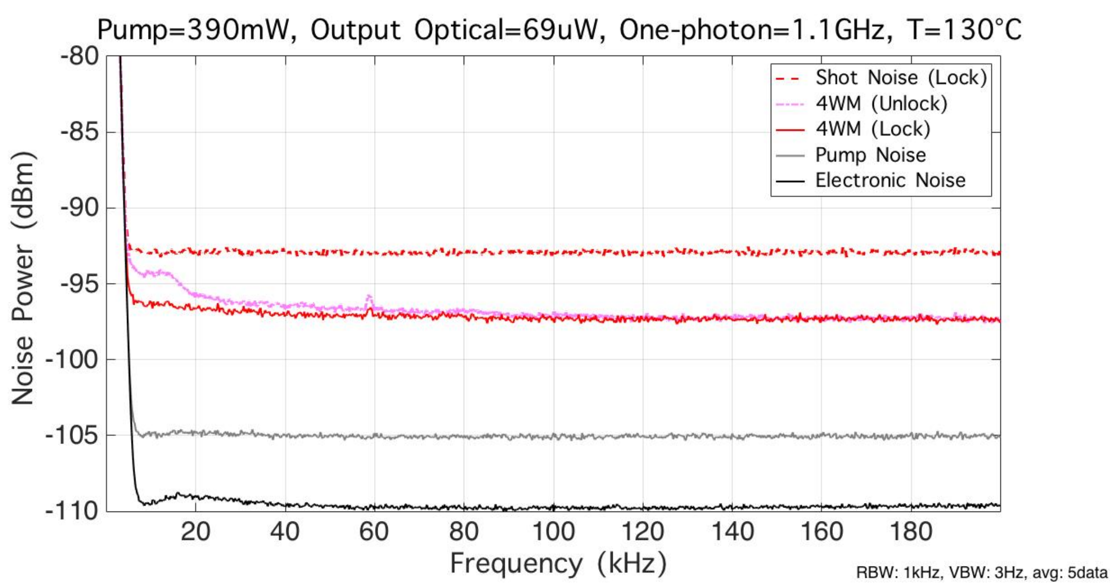

Figure 10. Squeezing versus frequency with the laser locked and narrowed, and unlocked and un-narrowed. Some improvements below 100 kHz were seen. Measurements at the lowest frequencies here were limited by the settings of the spectrum analyzer.

One of the main issues with our 4WM source is that the light (the pump, as well as the "twin" probe and conjugate beams) is all within a rather narrow frequency range of about 6 GHz. While Fabry-Perot-type filters can be constructed to separate frequencies that are only 3 GHz apart, they will typically have high losses (which would hurt any squeezing measurements), and rather limited in their spatial mode selection as well.

Since the flexibility of imaging the multiple spatial modes created in the source is one of its attractions, we would rather not spatially filter the beams in this way. Homodyne detection allows us to discriminate against the other frequencies, but is a much more complex detection method than direct detection. (The problem is mainly the depolarized, scattered, pump light appearing along with the probe and conjugate beams; since these beams are intrinsically weak and the pump is orders of magnitude stronger, a small amount of scattered pump light is often a problem, even with good polarization selection.) Thus, scattered light with the same noise spectrum as the pump can contaminate the measurements, and this is especially bad at low frequencies where technical noise on the pump laser is large.

One way to improve the discrimination against scattered pump light is to use a larger angle between the pump and probe beams, thus better enabling a physical filtering of the light with an aperture. The cost of this approach is a compromise on the momentum phase matching and coherence loss of the 4WM process. Increasing the angle much beyond 0.5 degrees leads to a decrease in the amount of squeezing due to the increased sensitivity to the Doppler effect (the extent to which the beams are non-co-propagating determines the ground state coherence dephasing rate, which reduces the squeezing). Theoretically [10] the gain should continue to increase as the angle is increased somewhat, and we do see this, however the squeezing is also affected by changing loss and decoherence rates. While this is always an issue, there is a range of angles where the trade-off between the reduction in squeezing "efficiency" as the phase-matching angle is increased is more than offset (at least at low measurement frequencies) by the decrease in noise due to the scattered light. The improvement is shown in Figs. 11 and 12 below. In these figures one can also see that the seeding beam for the probe in these experiments was not shot noise limited, creating an effect where a lower seed (and thus output) power leads to better squeezing as well.

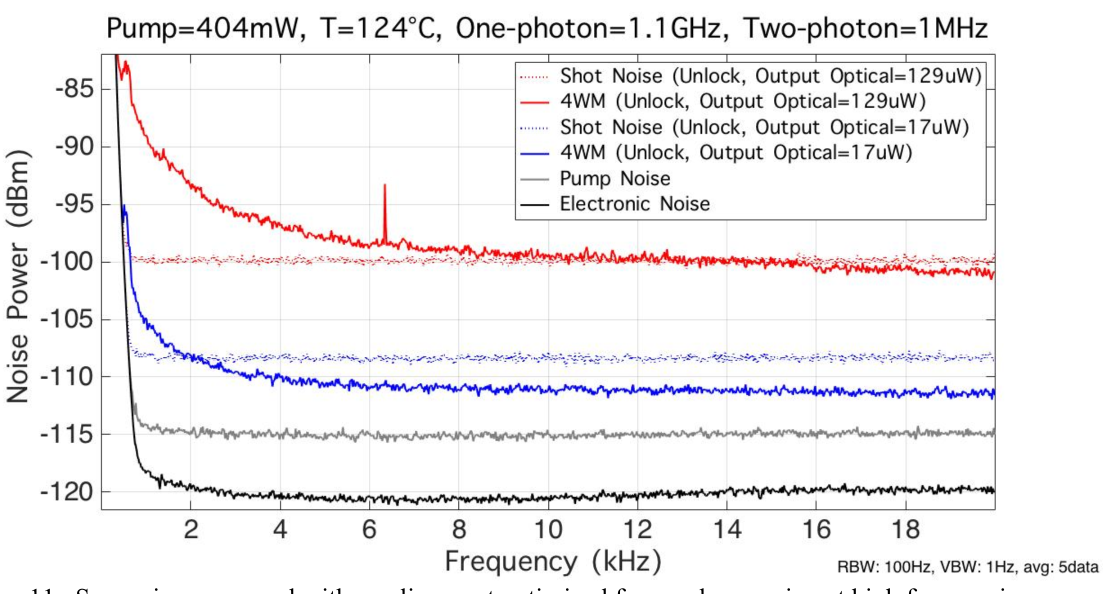

Figure 11. Squeezing measured with an alignment optimized for good squeezing at high frequencies (smaller probe-pump angle).

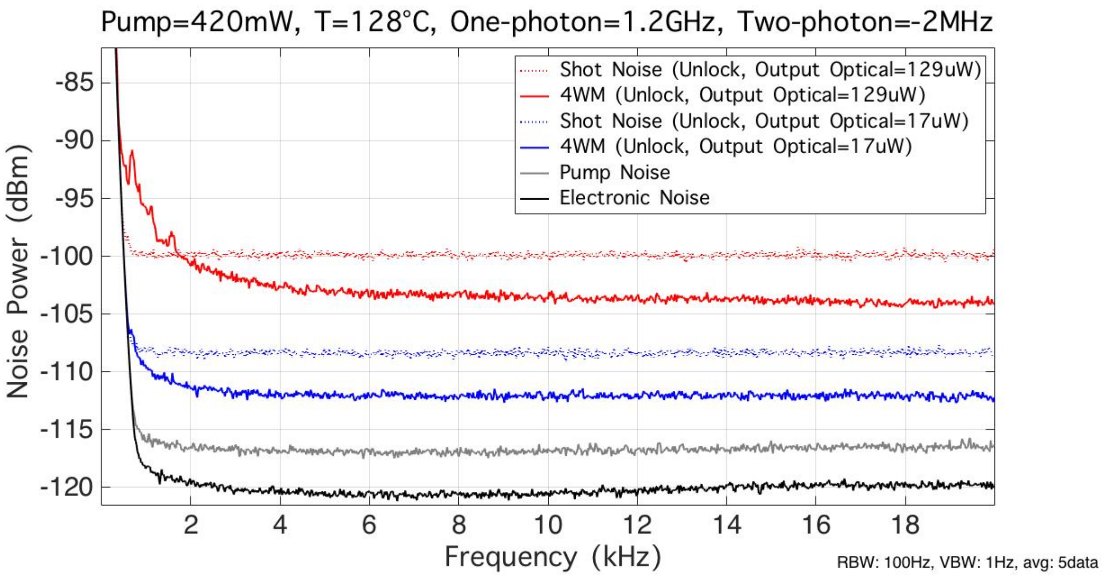

Figure 12. Squeezing measured with an alignment optimized for good squeezing at low frequencies (larger probe-pump angle). (The low frequency performance in this figure is limited by the spectrum analyzer settings.)

Thus, while mostly an engineering accomplishment, the attainment of low-frequency squeezing will be critical to our being able to apply squeezed light technology to problems in the real world. In addition, there has been some physical insight that has been gained in trying to understand the advances we have made. These studies constituted the preliminary work for the photodiode calibration project discussed in the next section.

Photodiode Calibrations

We have previously investigated the possibility of demonstrating a "twin-beam" technique for analog photodiode calibration [11] that is related to the photon-counting calibration technique based on spontaneous parametric down conversion [12] and other analog techniques [13]. In the photon-counting technique the production of pairs of photons in spontaneous parametric downconversion allows one to detect a photon in one beam and infer the presence of a photon at the other detector. The probability of detecting this photon then tells you the efficiency of the detector (after beam-path losses and other corrections are made). In the case of analog detectors where photon counting is no longer possible a similar technique is based on the idea that bright twin beams will be similarly highly correlated, and an upward fluctuation at one detector will be reflected in an identical upward fluctuation at the detector in the other beam. Measuring the auto- and cross-correlations will (again, after beam path loss corrections) allow one to extract the detector efficiencies. This technique would allow the dissemination of the calibration method, instead of having to disseminate calibrated artifacts in the form of detectors.

The accuracy of the calibrations is dependent on the degree of correlation of the "twin beams" used (equivalently, the degree of intensity-difference squeezing). Accuracies of 0.1% are sought after to be competitive with current techniques. The main issue preventing the comparison of the twin-beam technique with the current NIST calibrations (based on using a reference source calibrated with cryogenic radiometers) is

the fact that current measurements are made at frequencies of 200 Hz and below. Previous to this we had only demonstrated squeezing down to about 2 kHz. Now that we have squeezing down to 50 Hz we can proceed with a comparison. In our new labs we have begun to set up for a calibration of the beam-path losses and will proceed with calibration measurements when this is complete.

Optical Memory

We have continued to work on the gradient echo memory (GEM) in Rb vapor, and have made a spatially-addressable memory for "images" that is compatible with our 4WM source of entangled beams. This was reported in a paper in New Journal of Physics [14]. Unfortunately, we have found that there is optical gain in the memory itself, due to 4WM in the GEM as we have constructed it. This leads to noise that is sufficient to make the memory unsuitable for the storage and retrieval of quantum information. We know that one way to suppress this noise is to use the same polarization for both the stored signal and for the control beam used in the Raman transition for storage and retrieval. This frustrates the 4WM process and presumably suppresses it to a level where quantum information can be stored and retrieved from the memory. There is some controversy regarding this. Results from the Australian National University, where the GEM technique was originally developed, project low enough noise for quantum information storage, however, a group in Calgary, has results that imply that there will be too much intrinsic noise for this purpose. Unfortunately, using the same polarization for the signal and control beams, 1 GHz apart, means that they would have to combined and separated using cavities in our set-up, which will make using multiple spatial modes for these measurements difficult. We are building cavities that would allow us to perform these measurements but the apparatus has not yet been rebuilt in our new labs due to a lack of space and personnel at the present time.

Other

In addition to the projects mentioned above we have worked on a number of other projects involving non-classical light from 4WM that do not fit nicely into the above headings. An important concept in quantum information theory is the "quantum discord." This is a relatively recently-introduced concept that quantifies the difference between the classical mutual information and the quantum mutual information in bipartite systems. We showed how to measure it in a twin-beam system such as we have [2]. This will become important in our studies of the advance (or lack of it) of quantum information in a fast-light system.

We have also looked at the generation and distribution of random numbers using 4WM [15]. The random numbers can be generated by homodyning a random field, such as the vacuum field. Two-mode squeezed vacuum fields then allow us to generate and distribute correlated streams of random numbers. The random bits generated in the experiments are tested for randomness, and the correlations could be used for applications such as quantum cryptographic key distribution.

SU(1,1) interferometer

Under other funding we are building a nonlinear optical interferometer known as an SU(1,1) interferometer [16]. It is similar in construction to a Mach-Zehnder

interferometer, with the beamsplitters replaced by 4WM interaction cells. A quantum state with correlated pairs of photons in each arm is launched into the interferometer and at the output of the interferometer the correlated photon pairs are recombined to produce pump photons. The advantage of this interferometer is that it is predicted to be able to demonstrate 1/N scaling for phase sensitivity for N photons transiting the interferometer, as opposed to the 1/(root(N)) shot-noise limit of the conventional Mach-Zehnder interferometer.

While a group in Shanghai has already constructed such an interferometer, they have only demonstrated the achievement of interference fringes from it and have not demonstrated any phase measurements or the appropriate scaling, which we hope to do. We have an operating interferometer and are attempting to do a proper SNR analysis at this time.

We have done some theoretical investigations in conjunction with this grant to discover the effect of losses on the performance of the interferometer [17] and recently we have performed a number of simulations that have led us to propose different interferometer designs and compare different detection schemes. We are preparing to write up our simulation results related to this problem now.

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Abstract

Interest in the field of quantum optics has largely been motivated by demonstrating the unique features of the quantum world in the context of light. Taking advantage of these quantum properties of light to make advances in the context of metrology and measurement science has been the practical goal of our lab, and of the work supported under this grant. In particular, while many groups have worked toward demonstrating quantum features of light and how they can be used to advantage in fundamental scientific as well as some practical experiments, it has often been in the restricted context of a single spatial mode. In imaging terms this means a single "pixel" in an optical system. Our goal has been to attempt to expand the quantum advantages into multi-pixel imaging applications as well as to improve and simplify some of the single-spatial-mode applications of squeezed light through the use of four-wave mixing (4WM) in atomic vapors. We have worked to study the propagation of quantum correlations, improve low-frequency squeezing, demonstrate phase-sensitive optical amplification and its applications, and demonstrate a method for calibration of the absolute quantum efficiency of photodiodes. We have demonstrated intensity-difference (two-mode) squeezing to frequencies below 50 Hz, which will be used for photodetector calibration and imaging experiments. We have studied the propagation of quantum information through a phase-sensitive

optical amplifier and used this amplifier to implement a "perfect detector" for a single-quadrature signal. We have also used the phase-sensitive amplifier to characterize phase and amplitude modulation in an optical signal.

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2. Clark, J., Glorieux, Q. & Lett, P. D., "Spatially addressable readout and erasure of an image in a gradient echo memory," New J. Phys. 15, 035005 (2013).
3. Vogl, U. et al., "Advanced quantum noise correlations," New J. Phys. 16, 013011 (2014).
4. Clark, J. et al., "Quantum mutual information of an entangled state propagating through a fast-light medium," Nat. Phot. 8, 515 (2014).
5. Gupta, P., Horrom, T., Anderson, B. E., Glasser, R. & Lett, P. D., "Multi-channel entanglement distribution using spatial multiplexing from four-wave mixing in atomic vapor," J. Mod. Opt. 63, 185 (2015).
6. Li, T., Anderson, B. E., Horrom, T., Jones, K. M. & Lett, P. D., "The effect of input phase modulation to a phase-sensitive amplifier," Opt. Expr., to be published (2016).

2. New discoveries, inventions, or patent disclosures:
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No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

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none

Change in AFOSR Program Manager, if any:

none

Extensions granted or milestones slipped, if any:

A six-month no-cost extension was granted (our laboratories were moved to a new location during the grant period).

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Funding Summary by Cost Category (by FY, $K)

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